# Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

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Hydrogen Storage Engineering
CENTER OF EXCELLENCE

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OREGON NANOSCIENCE AND MICROTECHNOLOGIES INSTITUTE

MICROPRODUCTS BREAKTHROUGH INSTITUTE

# Overview

## Timeline

- Feb 1st 2009
- Jan 31st, 2014
- 0% Complete

## Budget

- Total project funding
  - DOE - $2,398,935
  - Contractor - $600,345
- Funding received in FY0 - $0
- Funding for FY09 - $300,000

## Barriers

- Barriers addressed
  - **A**) System Weight and Volume
  - **E**) Charging and Discharging Rates
  - **H**) Balance of Plant

## Partners

- **HSECoE Partners** - SNRL, PNNL, LANL, NREL, JPL, United Technologies, TRC, GM, Ford, BASF, Lincoln Composite, HSM, UQTR
- **Center Lead** - SNRL

# Hydrogen Storage Engineering Center of Excellence

**D. Anton, SRNL**
**T. Motyka, SRNL**

## *Materials Operating Requirements*

D. Herling, PNNL

- Materials Centers of Excellence Collaboration – SRNL, LANL, NREL
- Reactivity – UTRC
- Adsorption Properties – UQTR
- Metal Hydride Properties – SRNL
- Chemical Hydride Properties - LANL

## *Transport Phenomena*

B. Hardy, SRNL

- Bulk Materials Handling – PNNL
- Mass Transport – SRNL
- *Thermal Transport – SRNL,OSU*
- Media Structure - GM

## *Enabling Technologies*

J. Reiter, JPL

- Thermal Insulation – JPL
- Hydrogen Purity – UTRC
- Sensors – LANL
- Materials Compatibility – PNNL
- Pressure Vessels – PNNL
- *Thermal Devices - OSU*

## *Performance Analysis*

M. Thornton

- Vehicle Requirements– NREL
- Tank-to-Wheels Analysis – NREL
- Forecourt Requirements - UTRC
- Manufacturing & Cost Analysis - PNNL

## *Integrated Power Plant/ Storage System Modeling*

D. Mosher, UTRC

- Off-Board Rechargeable - UTRC
- On-Board Rechargeable – GM
- Power Plant – Ford

## *Subscale Prototype Construction, Testing & Evaluation*

T. Semelsberger, LANL

- Risk Assessment & Mitigation – UTRC
- System Design Concepts and Integration - LANL
- Design Optimization & Subscale Systems – LANL, SRNL, UQTR
- Fabricate Subscale Systems Components – SRNL, LANL
- Assemble & Evaluate subscale Systems – LANL, JPL, UQTR

## *Technology Area*

Technology Area Lead

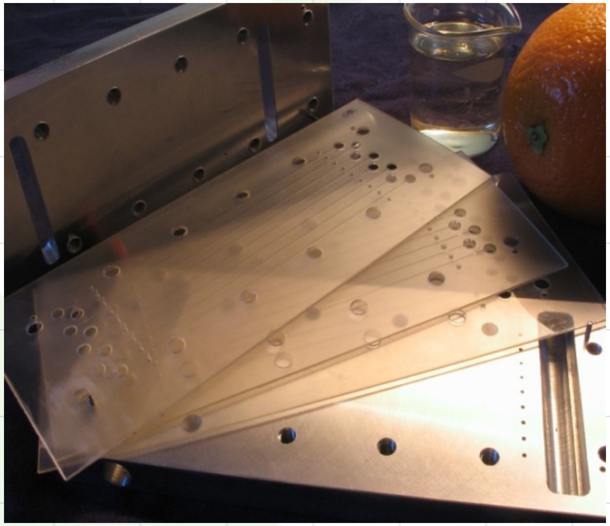
- Technology Team – TT Lead
- Technology Team – TT Lead
- Technology Team – TT Lead

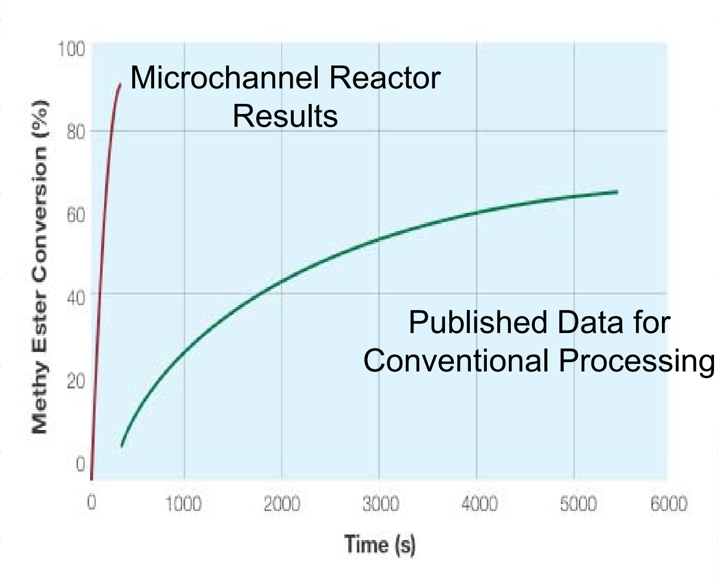
# Relevance -Objectives

- **Objective** – Use microchannel technology to …
  - 1) reduce the size and weight of storage,
  - 2) improve charging and discharging rate of storage
  - 3) reduce size and weight and increase performance of thermal balance of plant components.
- **Barriers Addressed**
  - Reduce system size and weight
  - Charging and Discharging rates
  - Balance of Plant

# Relevance – What is microtechnology-based Energy and Chemical Systems (MECS)?

- MECS uses microscale dimensions in flow paths (microchannels) to enhance heat and mass transfer
- For processes limited by diffusion, laminar flow residence time (and to some extent size) decreases as **$D^2$** where **D** is channel width. **In many energy and chemical systems, diffusion is the limiting phenomena. The use of microchannels addresses this barrier**





# Relevance – MECS Features and Hydrogen Storage

- Significant reduction in size and weight when a process is limited by diffusion
  - **Reduce storage size and weight related to heat and mass transfer**
  - **Reduce size of balance of plant thermal components**
  - **Reduce charging time**
- High degree of control over process
  - **Optimize storage for weight minimization**
- Number up rather then scale up
  - **Maintain optimum performance attained in single cell**
- Complexity can be added without increasing cost
  - **Integrate hydrogen distribution in cooling surfaces**
- Low thermal mass and high heat and mass fluxes will allow rapid start-up and response to transients
- In the temperature range of interest, attractive high volume manufacturing options exist.

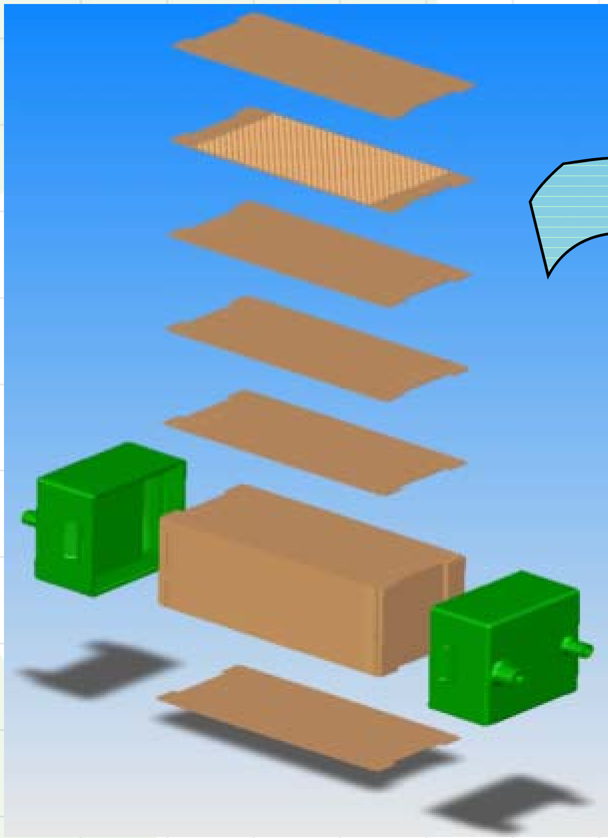
# Approach - Programmatic

- **Phase 1: System Requirements & Novel Concepts**
  - OSU will focus on simulation conducted to identify and prioritize opportunities for applying microscale heat and mass transfer techniques.
  - Working with other team members, OSU will identify the highest value applications and, where necessary, conduct experimental investigations and use modeling to collect data necessary to support the Go/No-Go decision to proceed to Phase 2.
- **Phase 2: Novel Concepts Modeling, Design, and Evaluation**
  - For each high-priority application, OSU will develop predictive models, design and evaluate components, fabricate proof-of-principle test articles, conduct proof-of-principle tests, and use the results to validate the predictive models.
  - With other team members, OSU will select one or more high-priority components for prototype demonstration.
- **Phase 3: Subsystem Prototype Construction, Testing, and Evaluation**
  - For each high-priority component, OSU will design, optimize, and fabricate the component.

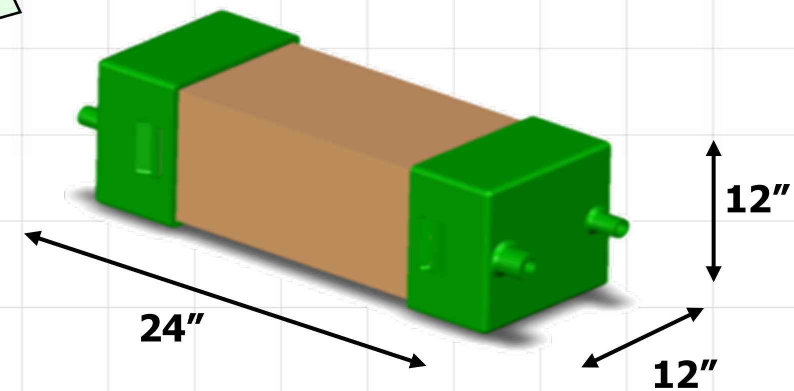
# Approach – Technical

- For each high priority component, where possible, use microchannel technology to reduce barriers to heat and mass transfer.
- Optimize the performance of a single unit cell (i.e microchannel) and then "Number Up"
- Use simulation validated by experimental investigations to conduct optimization
- Explore microlamination as a path to low cost high volume manufacturing

# Approach – Fabrication
## [Paul et al. 1999, Ehrfeld et al. 2000*]



**Microlamination of Reactor**




**Microchannel Reactor**

* W. Ehrfeld, V. Hessel, H. Löwe, Microreactors: New Technology for Modern Chemistry, Wiley-VCH, 2000.

# Approach – Second law Analysis

- Energy flows do not have equal value. The useful fraction of an energy flow is exergy (or availability etc.)
- Exergy is destroyed by irreversibility in any real process
- Exergy is a **common currency** that lets us combine the impact of any thermodynamic loss mechanism.
- Example: heat exchangers have two loss mechanisms, viscous dissipation (pressure drop) and heat transfer across a finite temperature difference. How do we combine these?
  - Traditional first law methods for assessing heat exchanger enhancements actually can give the wrong answer!
  - Both heat transfer and viscous dissipation can be evaluated as exergy destruction and combined into a correct figure of merit
- Second Law analysis can give a more accurate picture of sources of losses and hopefully suggest design improvements to minimize losses

# Approach – Milestones and Go/No Go Decision Criteria

- **2009/2010 Milestones**
  - Complete identification of the highest value applications of microchannel-based technology (2/1/2010).
  - Complete experimental investigations and modeling to collect data that will support the Go/No-Go decision to proceed to Phase 2 (11/1/2010).
- **Phase I Go/No Go Criteria**
  - Identify and demonstrate, through experiment and simulation, one or more high priority applications where the application of microchannel technology can make a significant contribution to meeting DOE 2015 performance goals
  - Develop specific performance, weight and size goals for each application included in the OSU phase 2 scope of work.
- **Phase II Go/No Go Criteria**
  - Complete successful proof of principle tests for high priority microchannel applications indentified in Phase 1 and demonstrate that based, on the proof-of-principle tests, a prototype microchannel component can meet the DOE 2015 goals.

# Technical Accomplishments

- This is a new project, funding for this project was available on April 1 2009
- Worked with other center members to identified two applications that merit additional investigation
  - MECS-based structured bed metal-hydride storage
  - Microchannel-based integrated hydrogen combustor/heat exchanger/recuperator plus other BOP heat exchangers
- Outlined fabrication strategy for MECS-based metal hydride storage concept

# Proposed Future Work

- MECS Metal Hydride Storage Concept
  - Use simulation to optimize unit cell
  - Experimentally validate simulation
  - Outline fabrication approach and production cost
- Integrated Combustor/Heat Exchanger
  - Use simulation to optimize integrated system
  - Fabricate technology demonstration
  - Experimentally validate simulation
  - Demonstrate rapid start-up and transient performance
- Second Law Analysis
  - Develop 2nd Law analysis tools for system simulation and CFD simulation
  - Use 2nd Law analysis tools to evaluate thermodynamic losses in hydrogen storage and identify design improvements

# Collaboration

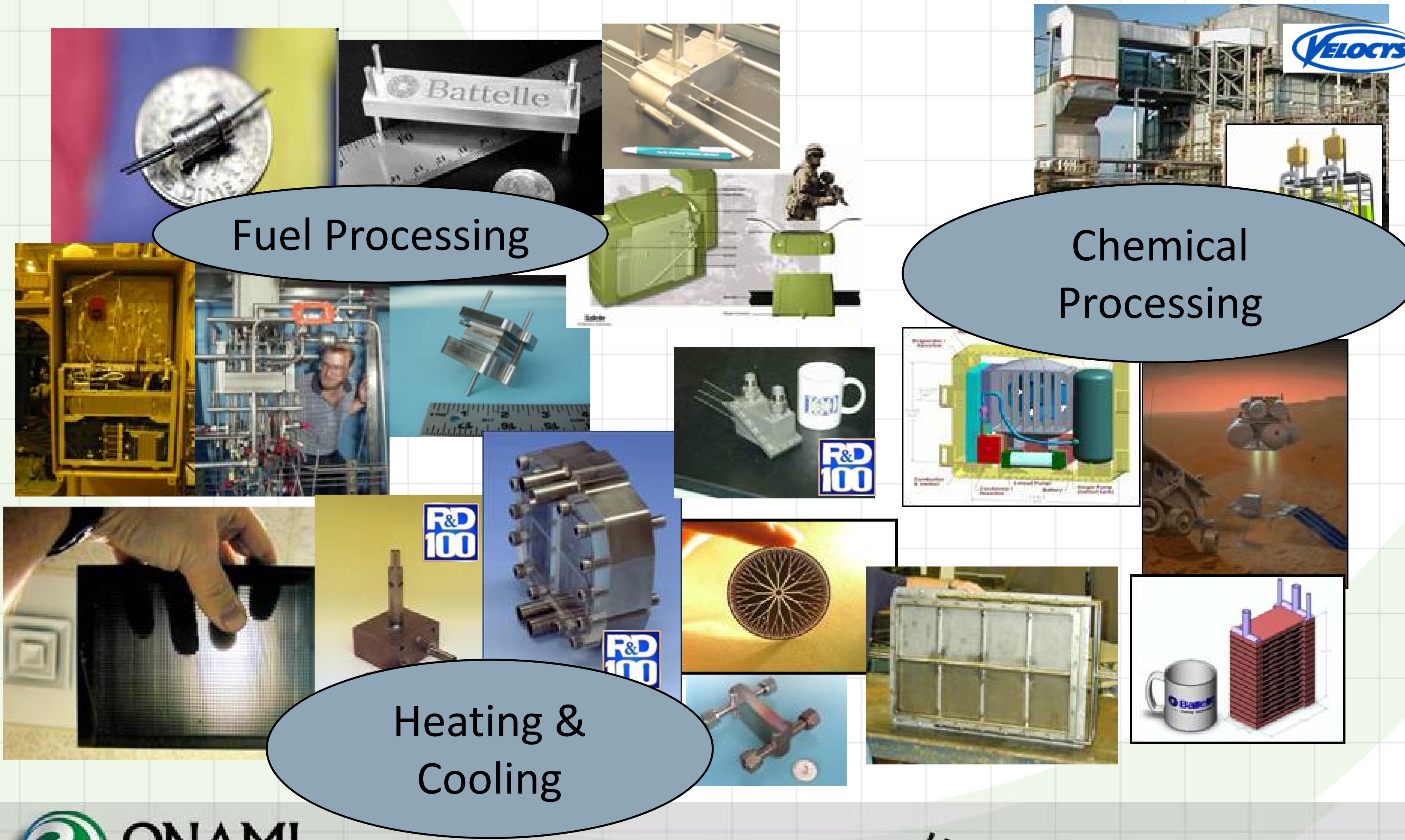
- Oregon State University is a member (a prime contractor) of the Hydrogen Storage Engineering Center of Excellence (HSECoE) which includes:
  - **Savannah River National Laboratory (Center Lead)**
  - **Pacific Northwest National Laboratory**
  - **Los Alamos National Laboratory**
  - **National Renewable Energy Laboratory**
  - **Jet Propulsion Laboratory**
  - **United Technologies Research Center**
  - **HSM Systems**
  - **Lincoln Composites**
  - **BASF**
  - **Universite' du Quebec a Trois-Rivieres**
  - **General Motors Company**
  - **Ford Motor Company**

# Project Summary

- **Relevance**: Microchannel technology can reduce size, weight and charging time of hydrogen storage.
- **Approach**: Use microscale diffusion lengths to improve diffusion limited processes and then "Number Up" rather then "Scale Up" to develop balance of plant thermal components and metal hydride storage bed.
- **Technical Accomplishments**: New Project
- **Collaboration**: Member of HSECoE team.
- **Proposed Future Research**: Develop microchannel-based concept for metal hydride and adsorption storage and key balance of plant thermal components

# Supplemental Slides

# What is MECS? - Applications



# What is the Microproducts Breakthrough Institute (MBI)

- The MBI is a unique 40,000 sq ft product development laboratory operated by Oregon State University (OSU) and the Pacific Northwest National Laboratory (PNNL)
- The MBI is focused on the application of process intensification to energy and chemical systems miniaturization
- The MBI combines the expertise of the leading industrial (PNNL) and academic (OSU) research programs on process intensification and is a national leader in developing this technology
- The mission of the MBI is to develop and commercialize miniature energy and chemical systems

# Why is 2nd Law Analysis Important to Hydrogen Energy Storage

- Hydrogen Storage is an extremely complicated thermodynamic process. For a metal hydride system requiring heating for desorption, the loss mechanisms include:
  - Irreversibility from pressure drop on heat source side of the device
  - Irreversibility from combustion not occurring at equilibrium temperature
  - Irreversibility from heat transfer across a finite temperature difference in heat exchanger and media
  - Irreversibility from desorption reaction
  - Irreversibility from diffusion of hydrogen in storage media
  - Irreversibility from pressure drop on the hydrogen side of the device

- While 2nd law analysis doesn't provide any new physics, it does
  - Give a clear picture of where losses are being generated
  - Provides a valid figure of merit for optimization
  - Our assumption is that the development of hydrogen storage will be accelerated by an accurate picture the magnitude and location of thermodynamic losses